

Arm Structure in Anemic Spiral Galaxies

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ABSTRACT

Anemic galaxies have less prominent star formation than normal galaxies of the same Hubble type. Previous studies showed they are deficient in total atomic hydrogen but not in molecular hydrogen. Here we compare the combined surface densities of HI and H₂ at mid-disk radii with the Kennicutt threshold for star formation. The anemic galaxies are below threshold, which explains their lack of prominent star formation, but they are not much different than other early type galaxies, which also tend to be below threshold. The spiral wave amplitudes of anemic and normal galaxies were also compared, using images in B and J passbands from the OSU Bright Spiral Galaxy Survey. Anemic galaxies have normal spiral wave properties too, with the same amplitudes and radial dependencies as other galaxies of the same arm class. Because of the lack of gas, spiral waves in early type galaxies and anemics do not have a continuous supply of stars with low velocity dispersions to maintain a marginally stable disk. As a result, they are either short-lived, evolving toward lenticulars and S0 types in only a few rotations at mid-disk, or they are driven by the asymmetries associated with gas removal in the cluster environment.

Subject headings: galaxies: clusters: individual (Virgo) — galaxies: evolution — galaxies: spiral — galaxies: structure

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1. Introduction

Galaxies with smooth spiral arms in their main disks on the Palomar Sky Survey were classified as anemic by van den Bergh (1976). He described them as spirals that are gas-poor with characteristics intermediate between S0’s and normal spirals.

Anemics are most often in rich clusters, but they are also in the field. The field population of anemics may not be different than normal galaxies because nearly all Sa galaxies, even those in the field, were classified as anemic by van den Bergh (1976) as a result of their generally indistinct spiral arms (Rubin et al. 1978; Bothun & Sullivan 1980).

Anemics in clusters seem to result from gas stripping (van den Bergh 1976). Not all clusters have HI deficiencies (Bothun 1982; Giovanelli & Haynes 1985), and even when they do there is not a good correlation between HI deficiency, red color, and anemic type (Kennicutt, Bothun, & Schommer 1984). In Virgo, where gas stripping is clear (Chamaraux, Balkowski, & Gérard 1980; Cayatte et al. 1994), the star formation rates and colors of stripped galaxies are about normal for their relative HI contents, and all three properties are similar to those of field galaxies with earlier Hubble types (Kennicutt 1983). This implies that stripping is a gradual process for a galaxy as a whole, mimicking in some respects normal galaxy evolution (Kennicutt 1983). Stripped galaxies that are anemics may be somewhat special, having radial orbits in the cluster (Vollmer et al. 2001a).

Gas stripping in clusters has a much more obvious signature in the distribution of the HI gas. Stripped galaxies in the centers of clusters have relatively small radii for their HI disks compared to their optical disk (Giovanelli & Haynes 1983; van Gorkom & Kotanyi 1985; Warmels 1988; Cayatte et al. 1994; Bravo-Alfaro et al. 2000), and where the HI remains, the HI surface density can be relatively low too (Kenney & Young 1989). Anemics have the largest HI anomalies, with the smallest relative HI radii and the largest inner disk HI deficiencies (Cayatte et al. 1994; Bravo-Alfaro et al. 2001).

Gas stripping in HI hardly affects the molecular mass and surface density, however (Kenney & Young 1989; Casoli et al. 1991; Boselli et al. 1997; Vollmer et al. 2001b). The H_2 mass may even be enhanced relative to HI in the inner regions, as if the increased pressure associated with stripping produces denser clouds (Kenney & Young 1989; Cayatte et al. 1994). This stripping pressure can also increase the star formation rates along the leading edges of galaxies if stripped gas falls back (Vollmer et al. 2001b), and it can make the inner CO disk asymmetric (Kenney et al. 1990; Hidaka & Sofue 2002).

Here we examine the surface densities at mid-radii for the total atomic and molecular gas in Virgo galaxies and other galaxies and compare them with the surface density threshold for star formation found by Kennicutt (1989). We find that the total surface

densities are below the threshold in the main disks of anemics, as is often the case for early type galaxies (Caldwell et al. 1991), but they exceed the threshold in later type galaxies. This threshold difference at mid-disk radius explains the low star formation activity in anemic galaxies.

The spiral arm strength in anemics is examined next using blue and near-infrared images from the OSU Bright Spiral Galaxy Survey. We find that anemics have normal arm/interarm contrasts for their spiral arm classes (grand design versus flocculent). The presence of normal stellar density waves in galaxies with low gas densities is unusual because gas is a strong amplifier for stellar wave instabilities (Bertin & Romeo 1988). Either the stripping process and the associated gas asymmetries (Kenney et al. 1990) are driving the stellar spirals, or the stripping took place very recently.

2. Gas Surface Densities in Anemic and Normal Galaxies

Anemic galaxies have normal total CO masses for their Hubble types (Kenney & Young 1989). Previous studies did not compare the H_2 surface densities in anemics and normal galaxies, nor did they compare the total atomic and molecular surface densities in anemic galaxies to the Kennicutt (1989) threshold for star formation.

The bottom panel in Figure 1 shows all of the detected H_2 surface densities, Σ , in the study by Rownds & Young (1999). Multiple detections in the same galaxy are plotted as multiple points, and non-detections are plotted at the bottom of the panel, where $\log \Sigma = -1$. The anemic nature of the galaxies was determined from the classifications in van den Bergh (1976) and van den Bergh, Pierce, & Tully (1990). Anemic galaxies are plotted with open circles in the figure (NGC 3718, NGC 4293, NGC 4450, NGC 4522, NGC 4548, NGC 4569, NGC 4579, NGC 4651, NGC 4689, NGC 4710, NGC 4826), and normal galaxies are plotted with dots. The abscissa is the morphological T type in the Third Reference Catalogue of Galaxies (hereafter RC3; de Vaucouleurs, et al. 1991); $T = 1$ is approximately equivalent to Hubble type Sa, $T = 8$ is equivalent to Sd. The conversion factor from CO to H_2 varies a little with Hubble type (Boselli, Lequeux, & Gavazzi 2002), as do fractional gas masses and other gas properties, so we plot all our results as a function of T type to remove these effects from our discussion. The figures indicate that there is no significant difference in the point-by-point distribution of H_2 surface density for anemics and normal galaxies. This is consistent with the lack of any such difference in the total H_2 mass and the average H_2 surface density (e.g., Kenney & Young 1989).

The top panel of Figure 1 shows the average central HI surface density versus the T

type for all of the galaxies in Warmels (1988) and Cayatte et al. (1994). This average is the integral of the radius times the HI surface density out to half of the optical radius ($D_0/4$ for corrected optical diameter D_0 in the RC3), divided by the integral of the radius out to this same distance (as tabulated by Cayatte et al. for their galaxies and calculated here from data in Warmels). The average surface density inside half the optical radius is usually representative of the inner disk surface density because the intensity of HI is relatively constant there. There is a well-known correlation between average HI surface density and morphological type, with later types having higher HI surface densities, and there is another well-known correlation with anemics having lower mid-disk surface densities than normal galaxies within a T type (Kenney & Young 1989; Cayatte et al. 1994). The anemics in this figure are NGC 4450, NGC 4548, NGC 4569, NGC 4579, NGC 4651, and NGC 4689.

The sum of the HI and H_2 surface densities determines the star formation properties in a galaxy. Kennicutt (1989) and Martin & Kennicutt (2001) found that stars tend to form where the summed surface density, Σ_{tot} , exceeds about 0.7 times the Toomre (1964) critical surface density, $\Sigma_{crit} = \kappa c / (3.36G)$, for an assumed velocity dispersion of $c = 6 \text{ km s}^{-1}$ and an epicyclic frequency κ derived from the rotation curve. To determine Σ_{tot} for this study, we used the average HI surface density inside $D_0/4$, as plotted in Figure 1, and the H_2 surface density at the radius $D_0/4$ from Rownds & Young (1999). We determined κ at $D_0/4$ from the HI rotation curves in Guhathakurta et al. (1988). There are 5 anemics in this overlapping sample, NGC 4548, NGC 4550, NGC 4569, NGC 4579, and NGC 4689.

Figure 2 suggests that anemics are not significantly different from other early-type galaxies, which all have a low ratio Σ/Σ_{crit} , as found by Caldwell et al. (1991). The low value of this ratio for anemics and other early types is the result of a moderately low H_2 surface density compared to that in later type spirals, a very low HI surface density, and a high κ in the early types, which comes from the relatively massive bulge.

Anemics have unusually weak star formation in their main disks, like other very early type spiral galaxies, because gravitational instabilities and other processes that normally promote star formation are not possible in these galaxies. This is true even though their total molecular masses are normal for their Hubble types. Part of the reason for the normal molecular masses in anemics is their higher molecular fractions at mid-disk radii (Kenney & Young 1989; Casoli et al. 1991). The motion of the anemics through the intergalactic medium causes higher disk pressures even in parts of the disk where it does not strip the gas away. Higher pressures are generally associated with greater molecular fractions as a result of increased cloud densities and self-shielding (e.g., Hidaka & Sofue 2002). Most of the extra molecular material is probably in the form of diffuse molecular clouds, which do not form stars.

Some anemics have active star formation in their inner regions, typically within $0.2R_{25}$. For example, NGC 4548, a strongly barred anemic galaxy, has star formation knots in the spiral arms at the ends of the bar. NGC 4580 and NGC 4689 have circumnuclear rings of star formation and smooth arms elsewhere. We have not checked if the gas surface density exceeds the critical threshold in these inner regions. Our results apply only to the mid-disk positions, where HI and CO data are available.

Guiderdoni (1987) originally suggested that surface density might provide a threshold for star formation, based on the HI surface densities in anemics. He considered an absolute threshold rather than a dynamical one that varies with κ , and did not include H_2 , but he was essentially correct in his conclusions about star formation.

3. Spiral Arm Strengths in Anemic and Normal Galaxies

3.1. Observations

Anemic galaxies have spiral arms, so the lack of star formation could in principle be related also to a low spiral arm strength. To check this, we measured arm-interarm contrasts in B and J bands for all the galaxies in Virgo that were observed as part of the Ohio State University Bright Spiral Galaxy Survey (Frogel, Quillen, & Pogge 1996; Eskridge et al. 2002). For those galaxies in which J-band data had poor flat fields or were unavailable, K or H band data were substituted. The images were obtained with the 1.8-m telescope at Lowell Observatory and the 1.5-m telescope at Cerro Tololo Inter-American Observatory, using the Ohio State Infrared Imager/ Spectrometer (OSIRIS) and the Cerro Tololo Infrared Imager (CIRIM). The plate scale is between 1.05 arcsec and 1.55 arcsec per pixel in J band for the different instrument/telescope combinations. NIR passbands are particularly useful for highlighting the underlying old stellar populations, with average ages in excess of 10^{10} yrs (see review in Frogel, Quillen, & Pogge 1996), whereas blue light is dominated by contributions from younger stellar populations.

Our sample consists of 30 galaxies: 12 anemics (classified by van den Bergh 1976) and 18 normal spirals, selected to have a wide variety of Hubble types, arm classes, and gas content. The OSU survey is magnitude-limited, and all anemic galaxies in that survey are included here. All galaxies with types S0 through Sb in our sample are barred or ovally distorted, while later types include nonbarred galaxies. The properties of the observed galaxies are listed in Tables 1 (anemics) and 2 (normal galaxies) with their NGC designation, morphological T type, optical arm class (from Elmegreen & Elmegreen 1987, where F is flocculent, G is grand design, and M is multiple arm), radius R_{25} (where the

surface brightness drops to 25 mag arcsec⁻²) in arcsec, arm-interarm magnitude contrast Δm in B and J bands, described below, and HI index (from RC3). High values of the HI index correspond to an HI deficiency.

The images were flat-fielded and sky-subtracted following procedures described by Berlind et al. (1997). Combined images were deprojected by using the position angles and inclinations listed in the RC3. Because this study considers only relative magnitudes, absolute calibrations were not necessary. A polar plot of (r, θ) , for distance r from the galaxy center and azimuthal angle θ around the galaxy, was made of each galaxy using a script written in IRAF. Azimuthal intensity cuts (corresponding to horizontal cuts on the (r, θ) plots) 3 pixels wide in radius were taken using the IRAF task PVECTOR. These cuts were repeated for several different radial distances from the center out to the optical edge of the galaxy at $\sim R_{25}$, in steps of 10 pixels in radius (approximately every 0.05 R_{25}). From these profiles, the arm and interarm intensities and their magnitude differences (arm-interarm contrasts) were measured. The results for each anemic galaxy were then compared to the results of normal galaxies of the same or similar type, considering also their arm class and HI index.

3.2. Arm-Interarm Contrasts

As described in the previous section, the arm-interarm contrasts were measured for this sample of galaxies at regularly spaced radii throughout the disk. These contrasts were found to have the usual properties, namely, they are larger in grand design galaxies than in flocculent galaxies, they increase with radius for non-barred galaxies and decrease with radius outside the bar for barred galaxies, and the arms are bluer in flocculent galaxies than in grand design galaxies. In addition, the blue arm-interarm contrasts fluctuate with radius much more in normal galaxies than in anemics, which is an obvious result of the smoother arms in anemics. The radial fluctuations of blue arm-interarm contrast for grand design normal galaxies is ± 0.7 mag, while in grand design anemic galaxies it is ± 0.1 mag.

The average arm-interarm B-band and J-band magnitude contrasts are shown as a function of galaxy T type in Figure 3, separated into different panels by color (top is blue and bottom is J) and arm class (left is grand design or multiple arm, right is flocculent). Normal galaxies have solid symbols and anemic galaxies have open symbols. The grand design and multiple arm galaxies of all Hubble types, whether anemic or normal, have higher average arm-interarm contrasts than the flocculent galaxies. For either arm class, there is no distinction in arm-interarm contrast between anemic and normal galaxies. Rubin et al. (1978) also noted that the arm-interarm contrast in an anemic galaxy looked normal.

This result implies that density waves in anemic galaxies are as strong as density waves in normal galaxies. Anemic structure is therefore the result of a low $\Sigma_{tot}/\Sigma_{crit}$.

4. Discussion and Conclusions

Anemic galaxies are spiral galaxies of normal size that have lost gas over time from a combination of internal star formation and tidal stripping. They have normal spiral density wave properties, but those in clusters have truncated outer HI disks and low total gas surface densities. Their main disk spiral arms are smoother than usual because of a lack of giant HII regions and star complexes, but they have approximately normal star formation rates and colors for their gas content, i.e., normal star formation efficiencies (as determined from data in Rownds & Young 1999).

The lack of star formation in anemics seems to be the result of their low Σ/Σ_{crit} . This is the first check on the utility of this star formation criterion that does not rely on a comparison between galaxies of intrinsically different types or between star formation regions with very different radii in a galaxy. For example, other studies of $\Sigma_{tot}/\Sigma_{crit}$ emphasized the outer parts of late type spirals (Kennicutt 1989; Martin & Kennicutt 2001) or nuclear starburst regions (Shlosman & Begelman 1989; Elmegreen 1994), or they were for elliptical galaxies (Vader & Vigroux 1991) or low surface brightness galaxies (van der Hulst et al. 1993). Here we see the effects of decreasing Σ/Σ_{crit} over time throughout the whole disk in an otherwise normal galaxy. When Σ/Σ_{crit} drops below 0.7 as a result of gas stripping or other gas removal processes, the star formation rate per unit area drops and the giant HII regions and OB associations disappear.

The future of anemic galaxies may be understood from numerical models of disk galaxies that have no source of cooling for the stellar population and no continuous supply of fresh stars with low velocity dispersions. In these models (Sellwood & Carlberg 1984; Fuchs & von Linden 1998), the stellar disk rapidly heats up and the spiral waves stop. Anemics are therefore evolving toward lenticulars or S0's as a result of their low gas abundance. The observation of strong spiral waves in severely stripped galaxies also implies three other things: (1) stellar spirals need stars with low velocity dispersions and cool gas mostly in their inner regions, which are still not heavily depleted in anemics; (2) the stripping probably occurred within the last few orbit times at mid-disk radius because spiral wave amplification gets weak quickly when both the stellar and gaseous disks are Toomre-stable (Jog & Solomon 1984; Bertin & Romeo 1988), and (3) the stripping process may itself drive spiral structure, perhaps through the asymmetric mass distribution of the stripped gas. Such asymmetries are present in both the HI (Boselli et al. 1994; Bravo-Alfaro et al. 1997,

2000) and CO (Kenney et al. 1990).

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Table 1: Anemic Galaxies

Name	Type	Arm Class	R_{25}	Δm_B	Δm_J	HI
1302	RSBR0	F	116.7	0.70	0.43	—
4314	SBT1	G	125.8	2.10	2.00	1.2
4457	RSXS0	G	80.8	—	0.64	—
4548	SBT3	G	161.1	1.33	1.22	3.91
4580	SXT1	M/F	62.7	0.87	0.57	4.91
4643	SBT0	G	92.7	1.80	1.34	—
4651	SAT5	M/F	119.4	0.80	0.36	1.86
4689	SAT4	F	128.0	0.34	0.43	3.22
4691	RSBS0	G	84.6	1.73	1.36	—
4699	SXT3	F	114.1	0.48	0.25	3.08
4941	RSXR2	M	108.9	0.55	0.26	3.45
5101	RSBT0	G	161.1	1.46	1.13	—

Table 2: Normal Galaxies

Name	Type	Arm Class	R_{25}	Δm_B	Δm_J	HI
NGC 0157	SXT4	G	125.1	1.20	0.76	2.11
1792	SAT4	M	157.4	1.00	0.52	2.9
3684	SAT4	F	92.7	1.20	0.40	1.41
3810	SAT5	F	123.0	0.89	0.50	2.17
4051	SXT4	G	157.4	1.40	0.85	2.41
4145	SXT7	M	176.7	0.65	0.45	1.29
4212	SA5	M	94.86	1.30	0.67	—
4254	SAS5	M	161.1	1.02	0.80	2.26
4303	SXT4	M	194.0	1.20	0.94	2.14
4394	RSBR3	G	108.9	—	1.12	3.72
4414	SAT5	F	108.9	0.75	0.40	2.04
4571	SAR7	M	108.9	0.68	0.33	2.90
4665	SBS0	G	114.1	1.3	1.00	—
4775	SAS7	F	64.14	1.31	0.65	2.03
5248	SXT4	G	185.0	1.47	0.70	1.67
5676	SAT4	M	119.4	0.75	0.45	2.19
IC4444	SXT4	M	52.1	1.5	0.60	2.50
IC5325	SXT4	M	82.6	0.70	0.36	3.03

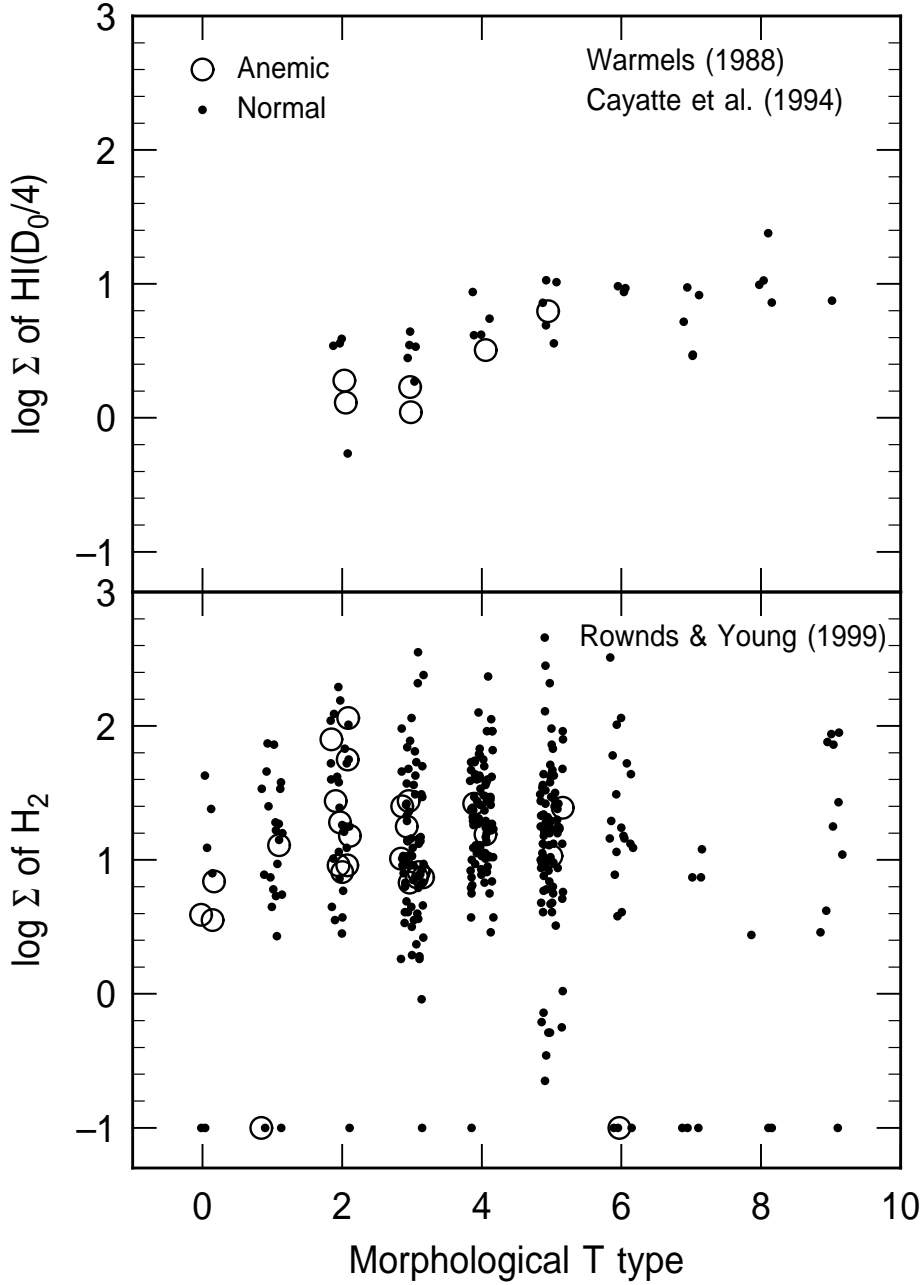


Fig. 1.— The surface densities in $M_{\odot} \text{ pc}^{-2}$ of the molecular (bottom panel) and atomic (top) phases in galaxies are plotted versus the morphological T type (1=Sa, 2=Sab, etc.), with early type galaxies on the left and late type galaxies on the right. Open circles represent anemic galaxies and dots normal galaxies. The points in the bottom panel include several different radii in each of 121 different galaxies; there are an average of ~ 4 points per galaxy, all from the study by Rownds & Young (1999). The points in the top panel are the average HI surface densities inside the half-light radii, from Warmels (1988) and Cayatte et al. (1994). The anemic galaxies have low HI average surface densities but normal H₂ surface densities for their T types, as noted in previous studies.

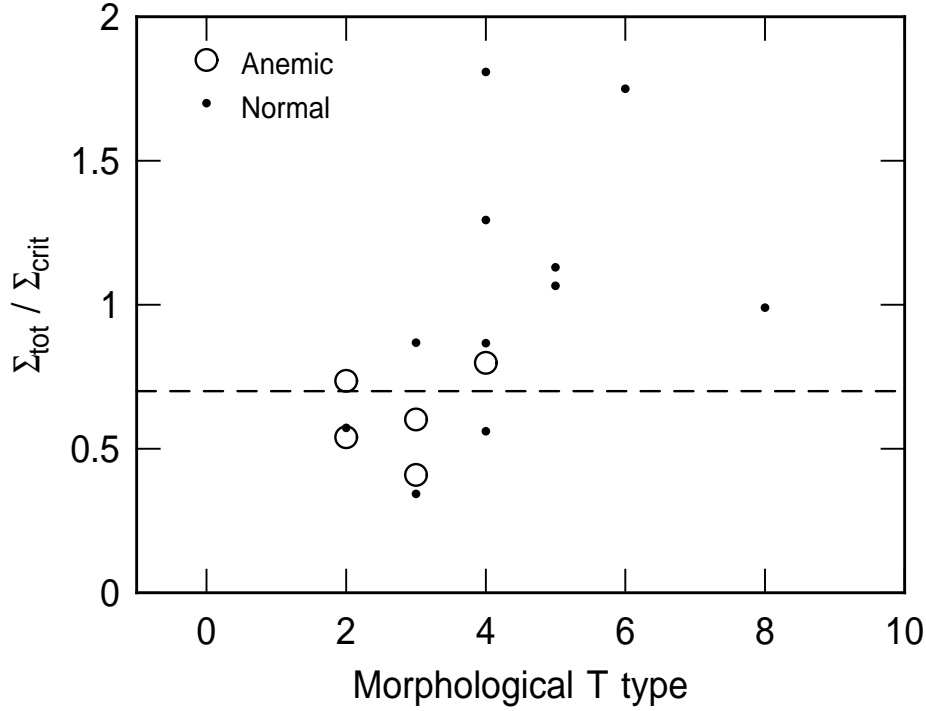


Fig. 2.— The ratio of the summed molecular and atomic surface densities from Figure 1 to the critical value, Σ_{crit} , is plotted versus the morphological type for all galaxies common to the studies by Warmel (1988), Cayatte et al. (1994), Rownds & Young (1999) and Guhathakurta et al. (1988). All quantities are evaluated at about half the optical radius. Anemic galaxies have surface densities below the threshold for star formation.

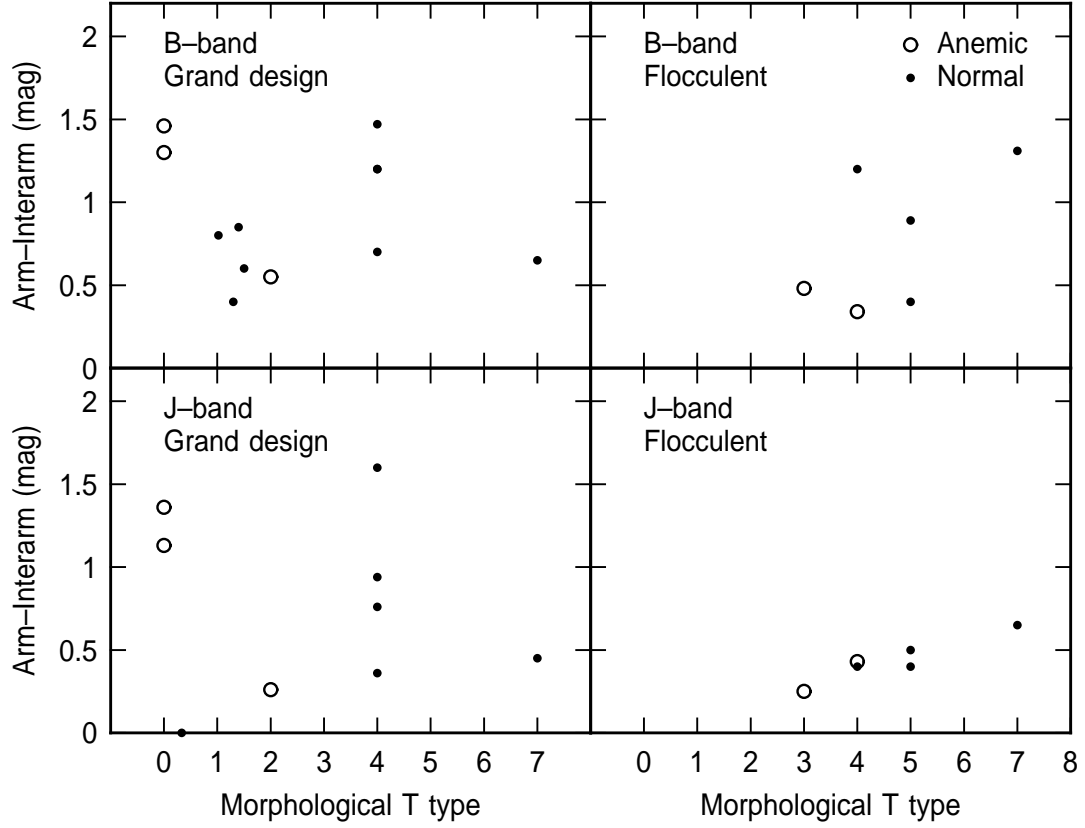


Fig. 3.— Arm-interarm magnitude contrast versus morphological T type for grand design and multiple arm galaxies on the left and flocculent galaxies on the right, in B passband at the top and J passband at the bottom. Anemic galaxies have spiral arm properties that are indistinguishable from normal galaxies.